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Research Article

Assessing ongoing risks and managing detections of non-native invertebrates in the Antarctic Region

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Abstract

The continent of Antarctica has remained relatively free of the impacts of invasive species to date. However, Antarctica is under increasing anthropogenic pressure from human activity and climate change, elevating the risk of alien species introductions. Scientific research and the maintenance of research stations by Antarctic Treaty Parties requires the transfer of large amounts of equipment and cargo, which can harbour biosecurity risk material. Here, we assess two decades of data collected by the Australian Antarctic Division on the detection of biosecurity risk material in its facilities and vessels, both during transport and in Antarctica. We use these data to identify emerging risk species or pathways, to compare the variability in detections over time and to construct a consequence table to facilitate effective responses and resource allocation to future detections, translating our research findings into guidance for decision-makers. We find that, despite the development of policy instruments, monitoring and management for the prevention of alien species introductions to Antarctica, the risk of introductions is ongoing. We highlight areas of concern, including the transport of live spiders and the continuing potential for cargo to harbour biosecurity risk material and the benefit of ongoing training and investment and support for staff and expeditioners in the reporting of non-native species detections. Finally, we provide tools and recommendations for decision-makers and on-ground managers in the Antarctic biosecurity space, based on our research. Future studies on the establishment risk of commonly transported species would assist in improving these tools.

Key words: alien species, Antarctica, biosecurity, non-native species management

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Introduction

Antarctica is the last continent on the planet that remains relatively free of the impacts of invasive alien species (Leihy et al. 2023). However, the Antarctic is experiencing increasing anthropogenic pressure from both human activity and climate change and new and uncertain threats are emerging, such as the transformation of habitats as a result of expanding ice-free areas (Lee et al. 2022a). Annex II to the Protocol on Environmental Protection to the Antarctic Treaty (Article 4) states that no non-native species shall be introduced to the land, ice shelves or water of

Antarctica without a permit (Antarctic Treaty 1991) (noting that this wording was intended to prevent intentional introductions and there is some uncertainty in terms of liability for accidental introductions (Hughes and Convey 2014)). Nevertheless, the unintentional transport of species and biological matter that are not native to the Antarctic and sub-Antarctic area, or biosecurity risk material (BRM) (which may include plant, animal and insect material, as well as pathogens, soil and water), continues to occur.

Non-native species are detected at various stages along transportation pathways to Antarctica, including within the cargo and packing facilities of national operators, on ships or planes en-route to Antarctica and within the station buildings and facilities on the sub-Antarctic islands and the Antarctic continent (Hughes et al. 2010, 2011; Houghton et al. 2016, 2019; Bergstrom et al. 2018; Remedios-de León et al. 2021). Antarctica's terrestrial communities have low species richness, simple community structure and narrow habitat ranges and the growing pressures of a changing climate makes them vulnerable to invasive species impacts (Convey et al. 2006). Biological invasions of Antarctica have resulted in the establishment of a number of non-native species in the warmer regions, in particular the Antarctic Peninsula and its islands, and the risk of the introduction of BRM to Antarctica continues to grow under increased anthropogenic pressure and climatic shifts (Hughes et al. 2015; Bergstrom 2022). The application of strict biosecurity measures, coupled with surveillance for high risk species by all stakeholders across Antarctica, is of paramount importance to reduce BRM introductions and invasions on the continent (Hughes et al. 2020).

To address the risk of non-native invasive species becoming established in Antarctica, a number of policies and guidelines have been developed for Treaty Parties. A primary resource for all Parties is the Committee for Environmental Protection (CEP) Non-Native Species Manual, which outlines key guiding principles to prevent unintended introductions of non-native species to the Antarctic Region, and the movement of species between biogeographic zones within Antarctica (Committee for Environmental Protection 2019b). Another key resource is the CEP Five-year Work Plan, released in 2019, which highlights the introduction of non-native species as a major priority from amongst a suite of environmental issues and concerns (Committee for Environmental Protection 2019a). Further, the Council of Managers of National Antarctic Programs (COMNAP), in conjunction with the Scientific Committee on Antarctic Research (SCAR), released a checklist for supply chain managers to assist in reducing the risk of transfer of non-native species to Antarctica by the National Antarctic Programs (Council of Managers of Antarctic National Programs 2010). Many of the Treaty Parties have also conducted research and developed individual biosecurity policies and protocols (e.g. British Antarctic Survey Biosecurity Regulations (British Antarctic Survey 2023)).

Australia has a long-standing history in Antarctica. Currently, Australia operates three active research stations on the continent and multiple planes and ship voyages to the continent throughout the summer season. Australian researchers have invested considerable effort in monitoring BRM in Australian facilities in the 21st century, particularly through the Aliens in Antarctica programme, an International Polar Year Program supported by multiple national operators, including the Australian Antarctic Division (AAD) through the delivery of the Australian Antarctic Program (AAP) (Whinam et al. 2005; Convey et al. 2006; Lewis et al. 2006; Chown et al. 2012; Huiskes et al. 2014; Houghton et al. 2016). In 2004, the

AAD established an internal database to record environmental incidents, including BRM and, in 2013, they set up a new cargo handling and biosecurity facility to more effectively combat the inadvertent transport of non-native species (Houghton et al. 2016). In 2019, an environmental code for participants in the AAP was published which highlights personal responsibility for biosecurity, and the AAD's current cargo biosecurity standard operating procedures were authorised.

The Aliens in Antarctica programme identified food as a high-risk vector for non-native species introductions to the Antarctic Region and cautioned that the transport of BRM would likely continue without the improvement of ship-based management, constant vigilance and surveillance across the transport pathway. Nearly a decade has passed since monitoring under the Aliens in Antarctica programme ceased. Currently, biosecurity at Australian Antarctic cargo facilities consists of deep cleaning, sight inspections before and after packing of cargo, rodent baiting and trapping in the facilities, as well as internal and external fumigation of packed cargo containers with a non-residual insecticide. All of these steps are preceded by an ongoing supplier awareness and education campaign on the importance of biosecurity. During transport and on arrival at Antarctic stations, biosecurity visual inspections are made at the time of unpacking cargo at the destination, in addition to routine searching and trapping along the transport pathway and passive baiting and trapping at AAD facilities in Antarctica. Sub-Antarctic Macquarie Island is home to Australia's fourth research station and has additional biosecurity requirements due to the AAD's responsibility to the department of Natural Resources and Environment Tasmania (NRE) to manage the environmental impact of its activities. Furthermore, the sub-Antarctic environment has an increased risk of non-native species establishment due to its warmer, wetter climate and increased rate of human occupancy relative to the continent (Frenot et al. 2005; Leihy et al. 2023). Particular attention is paid to break bulk cargo (i.e. individual cargo not stored in shipping containers) and cargo containing potential refuge for invertebrates, as well as the risk of rodent re-introduction following the success of rodent eradication in 2011 (Springer 2016). Consequently, on voyages bound for sub-Antarctic Macquarie Island, biosecurity detection dogs are used to search the cargo packing facility and inspect personal effects for rodents.

BRM detections in AAD facilities or vessels are primarily reported using the AAD's electronic environmental incident reporting system. If BRM is found, expeditioners, crew and staff are required to contain, treat and remove the hazard. They are then required to report the incident and monitor the area for any ongoing or additional BRM. Where required, follow-up actions and specialist advice from the AAD are recorded in the incident report. Although all incident reports receive a risk rating once reviewed by the AAD, to date, there has been no standard rapid response risk assessment protocol to assess each BRM detection on-ground at Antarctic stations and guide a consistent, appropriate response. As such, BRM detections during AAP activities in the Antarctic Region (particularly at Macquarie Island) are often treated as high-risk incidents. This can result in the halting of offloading or unpacking procedures for long periods of time. There is a clear need for a framework to define what is high and low risk BRM as they are detected on-ground in the AAD's operations.

Given that the amount of human and cargo traffic to Antarctica continues to increase, there is an increasing risk of non-native species being transported to the Antarctic Region (Hughes et al. 2020). This study aims to identify emerging risk

species or pathways that exhibit high propagule pressure. Further, we compare the variability in BRM detections over time with the uptake of policies and protocols designed to manage the risk of BRM to gauge their effectiveness. Finally, we use records of BRM detections from the last two decades to construct a consequence table to facilitate more effective responses and resource allocation to detections during the transport and offloading of cargo at AAD stations, translating our research findings into guidance for decision-makers.

Methods

Since 2004, scientists, staff and expeditioners on AAD voyages and stations have recorded non-native invertebrates and other BRM, such as plant matter or soil, through the environmental incident reporting system. All reports made relating to BRM detections since 2004 were extracted from this database. These reports were in relation to the four Australian Antarctic stations (Casey, Mawson, Davis and Macquarie Island), as well as vessels and aircraft travelling to these stations, noting that some vessels were chartered from other national operators. The notes of each report were read to determine (where possible) the location and habitat (e.g. consumables, cargo) of each BRM detection and whether the BRM comprised living or dead material. The month and year of detection was also extracted. These data were manually filtered to eliminate any duplicate reports or reports that did not relate directly to BRM. Reports made in the year 2023 were removed, to ensure that only complete years were captured through the study period. We present data on all forms of BRM reported; however, given that the majority of the reports pertained to invertebrates, only invertebrates were considered in the downstream analysis.

Sensu Houghton et al. (2016), where reports in the database identified the BRM as a "spider", "fly" or "moth" or other distinctive forms, the report was categorised by the appropriate taxonomic order (e.g. Araneae, Diptera or Lepidoptera). If no identification was provided in the report or if the identification was not deemed reliable due to the specimen having a non-distinct form, identification to taxonomic order level was made by studying supplementary photographs (where available). Identifications were made by MJH. If no photograph or formal identification was available and the specimen was non-distinct, the report was classified as "unreported". Where possible, each detection was classified as "live" or "dead", based on the information presented in individual reports. Pupae, egg sacs and cocoons were considered "live" only if found alongside live adult invertebrates. Live detections were then used to identify trends, as dead invertebrates were assumed to have died during the fumigation of cargo, in which case they were successfully managed by biosecurity protocol.

To identify non-linear trends in the BRM data over time, we implemented a generalised additive mixed model (GAMM) using the R package "mgcv" v.1.8-42 (Wood 2017). The number of detections per year was modelled over time, with year as the smoothing parameter and a Poisson response as appropriate for count data. Analyses of temporal patterns of BRM detections must take into account the intensity of human activity, as this is likely to increase the risk of non-native species introduction (Hughes et al. 2020). Therefore, as a proxy to account for the degree of human traffic and amount of cargo entering AAD facilities each year, the number of voyages per year were sourced from the AAP website (https://antapps.aad.gov.au/public/schedules/). Voyages were included if they stopped at one or more AAD station and were assigned to the year that they departed their home port.

The number of voyages per year (ranging from three to sixteen) was then used as an offset in the GAMM model.

To construct a consequence table that can be used to respond appropriately to invertebrate BRM detections during transport and offloading procedures, we designed a consequence matrix (modified from Fletcher (2015)), based on common BRM detections reported in the AAD environmental incident database and factors influencing the probability of a biological impact of BRM in Antarctica. Using a manual inspection of the reports within the database, a consequence table was designed with four levels of impact – minor, moderate, major and severe – which were assigned a score from 1 to 4. The criteria for the consequence of a biosecurity failing were informed by past reports, logical assessments and literature. We present the consequence table designed for continental Antarctica – sub-Antarctic Macquarie Island's environment requires an alternative approach due to the more habitable environment and higher risk of establishment of non-native species.

Results

Between 2004 and 2022, 251 BRM detections were reported in the environmental incident database, including amphibians, birds, mammals, plant matter and soil (Table 1). The dataset contained 205 reports of invertebrates that were used in subsequent analyses, 42 (20%) of which were previously included in Houghton et al. (2016). The four most prevalent invertebrate orders reported were Araneae, Coleoptera, Diptera and Lepidoptera, with Araneae and Diptera emerging as the most common taxonomic orders. Of these four taxonomic orders, Diptera and Lepidoptera were most commonly found in consumable supplies (such as fresh vegetables), while Coleoptera and Araneae were primarily reported as being found in cargo (Fig. 1A). Approximately 86% of reports documented detections at AAD stations, while the remainder occurred on ships travelling to the stations (with the exception of one pre-departure report which detailed contamination of fresh food at Tasmanian Shipping Supplies) (Fig. 1B) (for a full summary of locations, see Suppl. material 1). The highest number of reported BRM detections was at Casey Station (84 detections) (Suppl. material 1). Specimens from the four most prevalent taxonomic groups were more commonly reported alive than dead and were most often reported in the adult life stage (Table 2) (Fig. 1C).

Table 1. Summary of reports of biosecurity risk material made by AAD crew and expeditioners between 2004–2022.

Type of biosecurity risk material	Count	Percentage
Invertebrate	205	81.67%
Plant matter	25	9.96%
Feather	6	2.39%
Mammal	5	1.99%
Invertebrate sign (web/nest)	4	1.59%
Bird nest	3	1.2%
Amphibian	1	0.4%
Bird	1	0.4%
Soil	1	0.4%
Total	**251**	**100%**

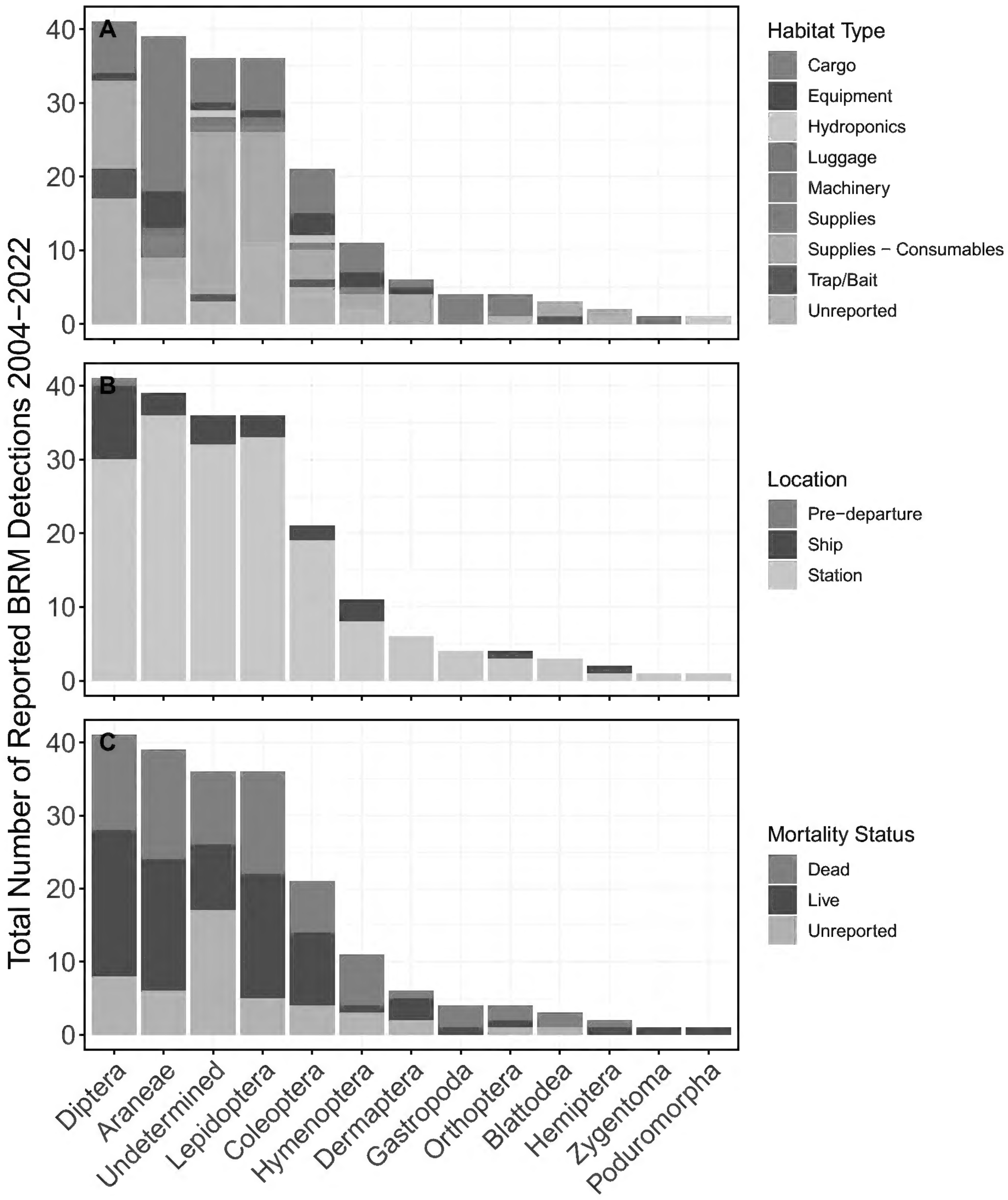

Figure 1. Proportion of biosecurity risk material (BRM) detections reported in various habitats (**A**), locations (**B**) and detection mortality status (**C**).

Table 2. Percentages of four most prevalent invertebrate groups reported alive, dead or unreported, along with life stages (pupae, cocoons and egg sacs were considered live if found in the presence of live adults).

Group	Alive	Dead	Unreported
Araneae	43.90%	36.59%	19.51%
	(94% adult, 6% egg sacs)	(94% adult, 6% egg sacs)	(72% adult, 14% egg sacs, 14% unreported)
Diptera	50%	30.95%	19.05%
	(95% adult, 5% unreported)	(92% adult, 8% unreported)	(87.5% adult, 12.5% larvae)
Coleoptera	47.6%	33.4%	19%
	(100% adult)	(100% adult)	(50% adult, 50% unreported)
Lepidoptera	46%	40.5%	13.5%
	(82% adult, 18% eggs/pupa/cocoon)	(93% adult, 7% larvae)	(80% adult, 20% pupa)

Live detections over time (Fig. 2A) were analysed using a GAMM, with annual number of voyages as an offset (Fig. 2B). The model indicated a significant variation in BRM detections over time (p < 0.001, df = 8.7); however, it had an adjusted R^2 value of -3.81, indicating that the model fitted the data poorly and is less accurate than the mean value of the dataset over time (i.e. a straight line) (Ozili 2023). Examination of the residuals indicated a high degree of variance from the model. An increase in reported live detections can be observed between 2010 and 2015, with the number of reports stabilising in recent years.

Consequence table

A consequence table to categorise BRM detections from minor to severe, based on their potential for impact, was developed. Examples of commonly reported BRM detection events are provided for each level of consequence, both during transport and during offloading procedures on arrival (Table 3).

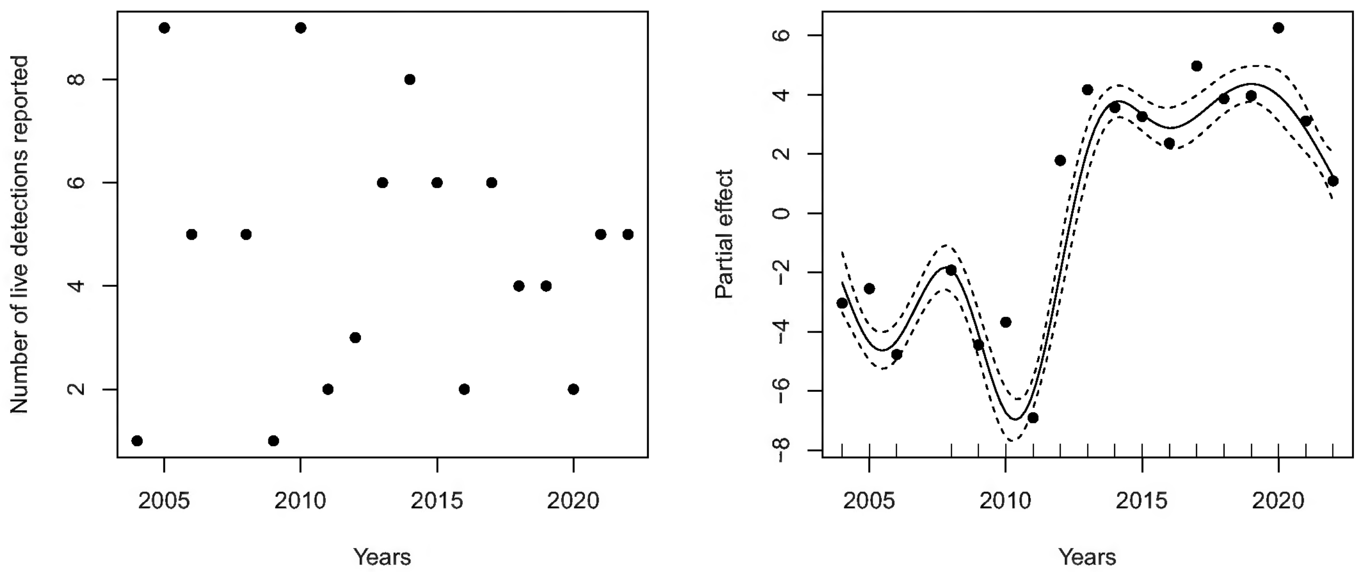

Figure 2. Number of live detections reported in the AAD environmental incident database over time (**A**) and GAMM analysis of detections with number of voyages per year as an offset (**B**) (95% CI).

Table 3. Consequence table for BRM detections along the transport pathway and during offloading procedures at continental Antarctic stations.

	Level of Consequence			
	Minor - 1	**Moderate - 2**	**Major - 3**	**Severe - 4**
Definition	Biosecurity risk material reaches Antarctica, but cannot survive in the environment.	Biosecurity risk material survives for a short time in the environment.	Biosecurity risk material survives for an extended period of time in the environment.	Biosecurity risk material survives and reproduces in the environment.
Event –Transport Pathway	• Dead invertebrates found in areas known to be fumigated/treated	• Dead or living invertebrates found in unfogged areas/cargo/food.	• Small number (< 10) of live crawling invertebrates found on cargo/plant equipment or on vessel	• Infestation (> 10) of live invertebrates found on cargo/plant equipment or on vessel
		• Includes spider webs/egg masses/insect larvae	• Live winged invertebrates found on cargo/plant equipment or on vessel	
Event – Offloading Procedures	• Dead invertebrates found in areas known to be fumigated/treated	• Dead or living invertebrates (less than 10) found in unfogged areas/cargo/food	• Egg masses/insect larvae found	• Infestation of live invertebrates within station (e.g. fresh food, dry goods, sewerage) – repeat event
		• Includes spider webs	• More than 10 live or crawling invertebrates found within station (e.g. fresh food, dry goods, sticky traps) – single event only	• Live invertebrates found external to station
Example Report	• Casey, 23/01/2021 – Alien invertebrate (moth)	• Mawson, 26/07/2018 – Spider found in science container	• Casey Station, 27/12/20 –Unknown alien larvae in celery	• Davis, 27/05/2014 – Live critters in hydroponics
	• Description: "Around 1630 hrs on Thursday 21-Jan-2021, an alien invertebrate (dead moth) was discovered in a shipping container between drums of ATK during the annual resupply operation".	• Description: "Whilst during fit-out in new science containers, a dead spider was found hanging in its web. Others were searched for but no others located".	• Description: "Around 1600 hrs on Friday 25-Dec-2020 in the Casey Mess, a small number of unknown alien larvae were detected in celery stems that were being chopped".	• Description: "Small dark critters found in hydroponics. They appear to live on the surface of the water and on the side of the tubs".
				• Note: Supplementary photo indicated that the invertebrates were springtails.

Discussion

We have observed an increase in the number of live detections of BRM along the Australian invasion pathway to Antarctica between 2010 and 2015, despite the advent of the CEP Non-Native Species Manual in 2011. A similar trend is apparent in detection data from Scott Base, an Antarctic base operated by New Zealand (Newman et al. 2018). Live invertebrates have continued to be detected at Australian Antarctic stations, indicating they have survived biosecurity treatment and the environment during the journey. Although the AAD established a new cargo facility and implemented a comprehensive biosecurity plan in the early 2010s, no consistent decrease in BRM detection is apparent in the data – though detections appear to have remained relatively consistent in recent years. It is notable that the CEP's 5-year Work Plan was released in 2019 and prioritised preventing the introduction of non-native species to Antarctica. Other relevant policy and protocol introduced by the AAD and AAP around this time include the environmental code for participants in the AAP (2019) and the current cargo biosecurity standard operating procedures (2019), which have contributed to enhanced biosecurity measures at the AAD's cargo facility in recent years. These policy instruments likely resulted in increased awareness amongst staff and expeditioners of the importance of catching and reporting non-native species.

It is difficult to draw robust conclusions from the GAMM analysis and identify direct causes for trends in the time series given the negative adjusted R^2 value and poor model fit, likely a result of the short time span (< 20 years) and relatively low sample size of this dataset. Further, a number of other factors may have influenced the number of BRM detections beyond policy and protocol. For example, no increase in reported live detections since approximately 2015 could be indicative of a change in search effort or reduced incentive to report BRM in the online system, such as reduced capacity amongst logistics staff and expeditioners to actively search for BRM during that year. Furthermore, we have no measure of surveillance effort for this period. While concern and vigilance for non-native species along the invasion pathway to Antarctica by National Antarctic Programs was heightened in the 2010s (Hughes and Pertierra 2016), priorities may have shifted with the operational and logistics challenges of the COVID-19 pandemic (Hughes and Convey 2020; Liggett et al. 2023). Notably, in a number of incident reports, the habitat of entrainment, mortality status and taxonomic form are not provided, limiting the potential for the identification of recurring risk pathways. Users of the environmental incident reporting system may, therefore, benefit from regular training, the introduction of mandatory fields to the incident reporting forms (including photographic evidence) and/or the supporting specimen identification materials, of a generalist nature, embedded within the reporting protocols.

Analysis of reports on BRM detections made using the AAD environmental incident database indicate that the most prevalent taxonomic orders are Diptera (flies) and Araneae (spiders). The invasive potential of flies in Antarctica has received ongoing attention in the scientific literature (Hughes et al. 2005; Volonterio et al. 2013; Potocka and Krzemińska 2018; Pertierra et al. 2021; Remedios-de León et al. 2021), but to date, there has been little assessment of the invasive potential of arachnids in the Antarctic Region (but see Pugh (2004)), noting that the Antarctic continent has no native spider species. The most common habitat of entrainment reported for Araneae is cargo and a high proportion of individuals

are found alive despite insecticide fogging of cargo within AAD facilities (Bergstrom et al. 2018). Houghton et al. (2016) identified live spiders reaching research stations as a notable result of their study – however, the rate of detection of live spiders in the AAD database remains at ca. 0.9 live spiders per year after 2013 when Houghton et al.'s study concluded, a slight decrease from ca. 1 per year prior to 2013. Biosecurity measures may, therefore, still require improvement if the Antarctic Treaty is to be adhered to and the risk of biological impact by spiders as a result of human activity in Antarctica is to be further reduced. Spiders introduced to Europe in containers or packaging material have been found to have a high establishment rate and it is generally believed within the pest control industry that fumigation is not always effective for spiders (Vetter et al. 2014; Nentwig 2015). A study on brown recluse spiders (*Loxosceles reclusa*) in the United States of America required fumigation of sulphuryl fluoride at ten times the required fumigation rate for drywood termites to effectively control spider infestations, with a higher dosage likely necessary to control egg sacs (Vetter et al. 2014). The high prevalence of non-native spiders found on cargo and alive, in or en-route to Antarctica indicates that further control measures may be required, such as more intense fumigation and the use of oil-based aerosols or dry-heat treatment to target egg sacs (Vetter et al. 2016; Hayasaka et al. 2021) – although it must be acknowledged that the risk of establishment of spiders in the Antarctic environment may not be significant.

Uncertainty remains as to which non-native invertebrates will survive in Antarctica; non-native springtails and mites are known to survive in the soils of the Antarctic Peninsula (Greenslade et al. 2012; Russell et al. 2013; Hughes et al. 2015), while others, such as the black fungus midge *Lycoriella ingenue* at Casey Station (Hughes et al. 2005), persist synanthropically within station buildings, where conditions are more mild than the external environment. The fate of these synanthropic species is uncertain, but at least one non-native fly on the Antarctic Peninsula (associated with research stations) is expected to have established in the natural environment and previously synanthropic species have become naturalised on several sub-Antarctic islands, including Macquarie Island (Frenot et al. 2005; Phillips et al. 2017; Remedios-de León et al. 2021). Whether spiders transported to Antarctica have the capacity to survive and establish in the surrounding environment is unknown. The extreme temperatures and lack of moisture in Antarctica are generally considered to be one of the primary barriers to invasive species establishment in the region; however, research suggests that some species of spiders, such as redbacks (*Latrodectus hasselti*), show little significant response to exposure to low temperatures, with the exception of some individuals moving more slowly (Smith et al. 2015). Further, populations of invasive Australian redbacks in Japan demonstrated higher fecundity at low temperatures than native populations, possibly as a result of selective adaptation during the invasion process or rapid adaptation in phenology (Mowery et al. 2022). Several species of wolf spider persist as predators in the Arctic tundra and so it is possible that some species of Araneae possess the necessary adaptations to survive in Antarctica's harsh conditions. This is particularly true for sub-Antarctic islands where native spider species occur (Pugh 2004) and the Antarctic Peninsula as the climate warms, moisture availability increases and ice-free areas increase (Lee et al. 2017, 2022a). Indeed, climate matching may precondition non-native spiders to successfully establish (Kobelt and Nentwig 2008), making cool-climate species from Tasmania a greater risk under climate-warming

scenarios. Further research, such as species distribution modelling, may provide more insight into the establishment risk of commonly transferred non-native invertebrates in east Antarctica.

Given the ongoing risk of inadvertent transfer of non-native species through operational activities in Antarctica, we harnessed reports of BRM detections made in the AAD environmental incident database since 2004 to create a consequence table that can be applied by operational staff on-ground to improve biosecurity procedures and resource use. Our study has highlighted that cargo and consumable supplies act as a conduit for a large proportion of BRM detected in the AAD's operations and we, therefore, suggest that these areas continue to be subject to a high degree of scrutiny for biosecurity personnel and decision-makers. We also found that the majority of BRM reports are made at Antarctic stations, indicating that most non-native species are either not detected until after cargo, supplies and luggage are unpacked and de-consolidated upon arrival, reduced access to and, thus, inspection of, cargo during voyages, or that BRM detected on transport vessels is not reported as vigilantly as those found within stations. Indeed, general biosecurity procedures on-board ships are not as strict as those implemented at the cargo facility or on station due to logistical constraints, despite the presence of lights, warmth and food sources to attract invertebrates. The proposed consequence table will enable rapid responses to detections during de-consolidation, but will also determine when ongoing monitoring is required to reduce the risk of additional BRM remaining undetected. It is recommended that the consequence table be reviewed decadally to keep pace with changes in processes that are expected to increase the risk of non-native species having a biological impact on Antarctica's ecosystems, including climate change, growing human activity, new infrastructure and increased transportation to and within the Antarctic Region (Chown et al. 2012; Duffy et al. 2017; Galera et al. 2018; Lee et al. 2022b). The consequence table has been designed to be easily implementable by end users of any level of expertise, enabling the implementation of a rapid response. Given the sensitivity of the Antarctic environment to non-native species, it is advised that staff continue to opt for management actions (e.g. thorough surveillance, deep cleaning, insecticide treatment and incineration of infested supplies (see Bergstrom et al. (2018)) associated with the highest level of perceived consequence, in line with the precautionary principle (Peel 2005; Peterson 2006).

We have shown that, while policy instruments for the prevention of BRM introductions into the Antarctic Region continue to be developed and enhanced, the risk of introductions is ongoing. While we detected no increase in reported BRM detections in the AAD's operations in recent years, the relatively small dataset and short time period of the study makes significant trends difficult to determine. It is clear, however, that the transport of non-native species to Antarctica remains a risk as anthropogenic activities continue in the region. The ongoing surveillance and documentation of BRM and continual improvement of BRM management and response by the AAP demonstrates its commitment to environmental stewardship and contributes to its status as a leading National Operating Party in the Antarctic biosecurity space. To continue to support best-practice biosecurity, we highlight areas of concern, including the continued transport of live spiders, the ongoing potential for cargo to harbour BRM, par-

ticularly during ship voyages to Antarctica where biosecurity scrutiny is lower than at departure and arrival, and the need for ongoing training and investment and support for expeditioners in the reporting of BRM detections. We present a consequence table for operational staff and decision-makers to apply on-ground, enabling rapid responses to BRM detections with an appropriate allocation of resources.

Recommendations for decision-makers

Based on the outcomes of this study, we make the following recommendations to national operators in Antarctica:

- Implement a comprehensive, mandatory biosecurity reporting system at all stages of the transport pathway to Antarctica (as is currently implemented by the AAP and AAD) and provide appropriate training on BRM detection, identification and reporting for staff, crew and expeditioners. Given the collaborative nature of the Antarctic Treaty System, the establishment of a shared reporting platform for all national operators in the future would encourage transparency, as well as facilitate the sharing of management strategies and training information between parties.
- Monitor non-native species entrainments for live transport of high-risk taxa (e.g. spiders) and revise biosecurity protocols where necessary.
- Implement a rapid response framework that will enable consistent, appropriate responses to detections of biosecurity risk material without compromising operations.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Author contributions

Conceptualization: ZTC, IRO. Data curation: IRO. Formal analysis: IRO, MJH. Methodology: IRO. Supervision: PC, JS. Validation: KL, MJH. Visualization: IRO. Writing - original draft: IRO. Writing - review and editing: MJH, PC, KL, ZTC, JS.

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Data availability

De-identified data used in this study can be accessed via the Australian Antarctic Data Centre (http://dx.doi.org/doi:10.26179/cdpm-g422).

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Supplementary material 1

Full summary of locations of biosecurity risk material detections by taxonomic order

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